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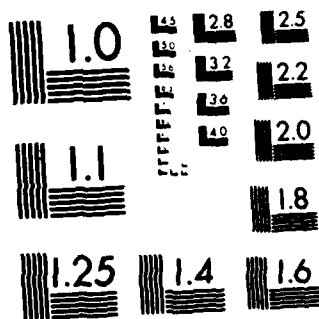
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LASER RESEARCH AT THE FRANK J. SEILER RESEARCH LAB

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Abstract

The Frank J. Seiler Research Laboratory (FJSRL) is an Air Force Systems Command (AFSC) organization charged with (1) planning and executing USAF research programs in aerospace-mechanics, applied mathematics and chemistry; (2) supporting research by USAF Academy faculty and cadets; and (3) functioning as the AFSC focal point for USAF Academy research and development efforts proposed for AFSC sponsorship. FJSRL is the only USAF basic research lab.

Within the Aerospace-Mechanics Directorate, we have two projects which are particularly suited to the total mission outlined above. These are the laser gyro and laser damage projects. We will discuss both the background and plans for each of these experimental research efforts.

Introduction

The laser gyro concept had early beginnings. In 1911 the French physicist, G. Sagnac, performed an experiment to measure rotation with an optical interferometer.¹ Some four years earlier Sagnac had predicted that counter rotating beams in a ring interferometer would experience different path length changes if the interferometer was rotated. This path length difference would manifest itself in the form of a fringe shift, ΔZ , which he calculated to be:

$$\Delta Z = \frac{4A}{\lambda_0 c} \cdot \vec{\Omega} \quad (1)$$

where \vec{A} is normal to the plane of the ring and is equal to the area of the ring, λ_0 is the vacuum wavelength of the light, c is the speed of light and $\vec{\Omega}$ is the rotation rate vector. His apparatus consisted of an 866 cm² ring interferometer and a mercury arc lamp. Using the indio line (0.42 μ m) and rotating first 2Hz one way and then 2 Hz the other, he was able to observe the predicted fringe shift of about 0.07 rad.

Use of this concept as a practical gyro didn't catch on until about 1960 when Rosenthal suggested a ring laser interferometer. Macek and Davis, at Sperry Gyroscope, took this idea and, in 1963, demonstrated the first active ring laser gyroscope (Figure 1). Here too the basis of operation is a path length difference. However, with the laser gain tubes as part of the ring, a path length change results in a shift in the laser oscillation frequency. A path length difference due to rotation will produce a beat frequency f which is given by:

$$\Delta f = \frac{4A}{\lambda_0 P} \cdot \vec{\Omega} \quad (2)$$

where P is the perimeter of the ring^{3,4}.

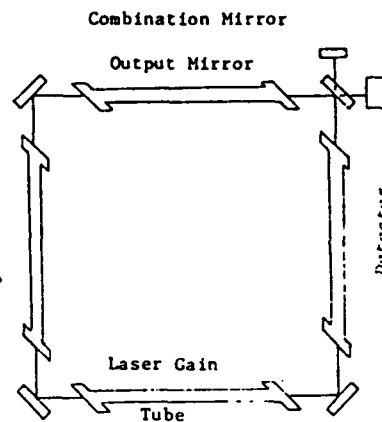


Figure 1

The first ring laser gyro was a 1 meter square and had a HeNe gain tube in each leg.⁴

The significant difference here is the much larger scale factor compared to Sagnac's device. There is, however, a problem with the active ring laser gyro that the Sagnac interferometer does not have. Backscattering off mirrors couples the two laser oscillation modes and when the Δf is small enough the two modes lock to a common frequency. Thus the active ring laser gyro has a deadband. Several solutions to this problem have been attempted and the Honeywell body dither approach has been quite successful. FJSRL is pursuing a scheme proposed by Ezekiel and Balsano² (Figure 2). This approach is more closely related to Sagnac's scheme in that the light source is external to the interferometer, but the mercury arc lamp has been replaced by a laser. Having the laser external to the ring avoids the frequency lock problem, and through the use of acousto-optic modulators, the change in path length is converted to an optical frequency difference which is identical to the beat frequency in the active ring laser gyro. Thus the scale factor gain is maintained.

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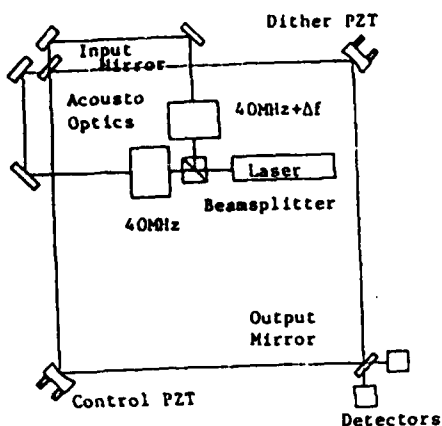


Figure 2

In the Ezekiel-Balsamo concept the CW beam resonance is maintained via path length control, while the CCW resonance is maintained via acousto-optic frequency shifting

The counter rotating beams are derived from a common single mode, single frequency laser. The "trick" is to keep both beams resonant in the ring. The resonance condition for the CW beam is maintained via a path length control loop. Figure 3 shows the intensity of the clockwise beam on the photodetector vs. the path length of the ring. The periodic nature is due to the fact that resonance occurs whenever the path length is an integral number of half wavelengths of the beam. The servo system maintains a maximum detector output. A small amplitude high frequency dither on one mirror position provides the capability to determine the sign of the displacement error. Corrections are then made by pushing, or pulling, on a second mirror. Both the dither and the correction movements are accomplished with piezoelectric translators (PZT).

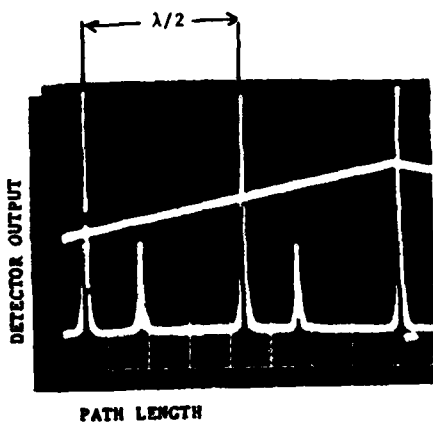


Figure 3

As the path length is varied the photodetector shows periodic resonances. Two modes are being excited in this resonator.

Since the pathlength change due to rotation is opposite for the two counter rotating beams, the correction for the CW beam only serves to worsen conditions for the CCW beam. The resonance condition for the CCW beam is maintained by adjusting its wavelength via the acousto-optic modulator. The CCW

detection scheme is the same as for the CW beam and a common dither serves well for both control loops.

The end result is that a rotation causes a path length correction for the CW beam and a wavelength correction for the CCW beam leading to a frequency difference between the two beams, which is proportional to the rotation rate (See EQ 2).

The optical design problems with this device are challenging. The resonant ring is an open electromagnetic waveguide whose dimensions are all large compared to the wavelength. It is a non-trivial problem to excite only a single mode in the ring. In general, several resonant modes will be excited by the incoming beam, despite the fact that the incoming beam itself is single mode. Ideally, only the TEM_{00} mode should be excited, but without taking precautions to match both the diameter and radius of curvature of the incoming beam to the resonator TEM_{00} mode, higher order resonator modes will be excited. These higher order modes oscillate at different frequencies than the TEM_{00} mode and thus cause a frequency pulling effect in the gyro. In fact several precautions must be taken to minimize the effects of these higher order modes:

- (1) Match the incoming beam to the TEM_{00} mode of the resonator.
- (2) Design the resonator such that the most troublesome modes are far removed from the TEM_{00} mode (in frequency).
- (3) Place apertures in the ring to "kill off" the higher order modes.

A combination of all three of the above strategies is required. Alignment of mirrors and maintenance of alignment is also critical.

We are currently building a $0.62m^2$ device at FJSRL. To support this effort we have developed a computer program which allows us to characterize the TEM_{00} mode of an arbitrary optical ring resonator. The program allows us to vary the geometry of the ring as well as the curvature of the mirrors. Thus it is useful for resonator design and aperture placement. Its primary use, however, is for mode matching. Given the specifications of the laser beam, the ring resonator and the mode matching optics, the program will verify how well matched the incoming beam is to the resonator TEM_{00} mode. It can further be used to check the sensitivity of the design to misalignments and other mechanical tolerances.

Another effort is underway to characterize the higher order modes. The main items of interest here are the resonant frequencies of the higher order modes and how energy couples into these modes.

When completed the $0.62m^2$ gyro will be tested on a computer controlled rate table. An error model will be developed and verified. Results of this program will be used as the basis for a much larger passive resonant ring laser gyro design.

Both electrical and optical considerations for even a moderate size device are challenging, but the potential rewards of successfully building a very large device are enticing. The sensitivity to rotation increases with size; a square ring, 10 meters on a side, has a theoretical sensitivity of 10^{-10} earth rate (1.5×10^{-9} Deg/hr), using a 4-watt frequency stabilized argon laser⁵. With such a device we would obtain a much better error model of the passive resonant ring laser gyro and also have a capability to investigate such effects as variability in the earth's spin rate and polar axis wobble. At FJSRL we have a unique isolation test pad facility that is vibration isolated (better than 10^{-8} g) and attitude stabilized (better than 0.001 sec) on which we can build a $37m^2$ device.⁶

Laser Damage of Dielectric Mirrors

The laser damage of dielectric mirrors is the other major laser experiment we have in our directorate at the Seiler Laboratory. We will modify a glass laser to operate at 1.3 μm to test dielectric mirrors which have been fabricated for iodine laser use. The iodine laser operates at 1.352 μm .⁷ The glass laser is an attractive alternative to using an iodine laser for the laser damage experiment. Here are some of the reasons:

(1) It will be easier to achieve a more uniform beam with a glass laser rather than an iodine laser.

(2) The safety hazards associated with a glass laser are much less than for an iodine laser; therefore, this system is more amenable for integrating cadets into our research.

(3) The cost of a glass laser system is less than for an iodine laser.

A major disadvantage of a glass laser over an iodine laser is the slow repetition rate of firing. After each shot, the glass must be allowed to cool. Although YAG would cool quickly, the costs to get YAG in adequate size for damage experiments would be prohibitive.

ND3+ Operating at 1.3 μm . The $4F_{3/2} - 4I_{13/2}$ transition contains the 1.319 μm of interest. The iodine laser operates at 1.315 μm . The literature is rich with operation of YAG at 1.3 μm .⁸⁻¹⁰ Marling reports tuning the YAG operation with an intercavity etalon.¹¹ Fernelius has used a CW YAG to measure bulk absorption at 1.3 μm .¹² Wiggins has addressed the applicability of using Nd instead of iodine.¹³ Wiggins measured the absorption of water at the iodine wavelength (1.3152 μm) and at Nd³⁺, with the iodine wavelength absorption being about 7% less. Therefore, if water is the main cause of absorption in the coating, the difference in the wavelengths should not be that significant.

Mauer has reported 1.37 μm operation of Nd³⁺ in a glass host, for the $4F_{3/2} - 4I_{13/2}$ transition.¹⁴ The wavelength was longer than 1.32 μm because of the peak of the reflectivity of the dielectric used to form the cavity.

Relative cross sections and measured relative room temperature cw laser threshold for Nd:YAG is given in Table 1 from Koehnner's work.

Table 1
Main Room-Temperature Transitions in Nd:YAG

Wavelength (μm)	Peak effective room temperature cross section (10^{-19} cm^2)	Measured relative room temperature cw laser threshold
$4F_{3/2} - 4I_{9/2}$		
0.939	0.81	
0.946	1.34	
$4F_{3/2} - 4I_{11/2}$		
1.0520	3.1	2.08
1.0551	0.20	
1.0615	6.65	1.15
1.0641	8.80	1.00
1.0682	1.10	
1.0738	4.00	1.22
1.0779	1.55	
1.1055	0.32	
1.1122	0.79	2.17
1.1161	0.77	2.26
1.1225	0.72	2.36
$4F_{3/2} - 4I_{13/2}$		
1.319	1.50	1.60
1.335	0.92	
1.338	1.50	2.17
1.342	0.63	
1.353	0.35	
1.357	0.88	

A review of reported 1.06 μm transitions in reference 10, showed only about ± 2 nm difference in wavelength from host to host. Snitzer has concluded, from the relatively constant ratios of the intensities of the fluorescent lines in various alkaline earth silicates, that the ratios of the matrix elements from the $4F_{3/2}$ state to lower states are taken to be independent of the host.¹⁵ Therefore, the cross-section results in Table 1 should also apply to glass lasers.

Laser Design Considerations for 1.3 μm Operation.

In order to achieve 1.3 μm operation, it is necessary to suppress the 1.06 μm transition. We used the 140 mm long, 12 mm diameter ED-2 laser glass in the Space Rays oscillator which is pumped by two linear flashlamps wired in series to a 750 μf capacitor bank which, when charged to a maximum 4 KV, has 6 KJ of stored electrical energy. Lasing was detected with a Molelectron Model P3 pyroelectric detector and a Hewlett-Packard Model 181A oscilloscope. The detector looked at an approximately 8% reflection from a glass beamsplitter. The threshold for lasing at 1.06 microns was a pump voltage of 2.1 KV when a 97% reflectivity back mirror and a 60% reflectivity front mirror formed the cavity. The threshold condition for lasing is:

$$R_1 R_2 T_1 T_2 \exp [2L(g-\alpha)] = 1 \quad (3)$$

where R_i is the reflectivity of the i th mirror, T_i is the transmission of the i th surface inside of the resonator, L is the length of the rod, and α is the loss per centimeter (0.005 cm^{-1} for ED-2) inside of the rod, and g is the gain per centimeter. The gain can be expressed as a function of the cross section for the transition σ , and the number of ions/ cm^3 , N , in an excited state

$$g = \sigma N. \quad (4)$$

If we operate in a region where N is proportional to the pumping energy, then we can express g in terms of the threshold value g_0 and the pumping energy of the capacitors E .

$$g = g_0 E \quad (5)$$

The threshold value g_0 at $1.06 \mu\text{m}$ can be related to the $1.32 \mu\text{m}$ threshold value by

$$g_{0,1.3} = \frac{\sigma_{1.3}}{\sigma_{1.06}} g_{0,1.06} \quad (6)$$

From our threshold measurement, we calculated g_0 at $1.06 \mu\text{m}$ equal to 1.6×10^{-5} .

We attempted to achieve $1.3 \mu\text{m}$ operation with a grating and dielectric mirror. The 600 lines/mm, replicated diffraction grating from PTR, was blazed to achieve 80% reflectivity in first order at $1 \mu\text{m}$. The output mirror was 45% reflective at $1.3 \mu\text{m}$. Equation 1 shows that, for our system, the minimum reflectivity of 85% for the output mirror at 4000 volts. We plan to use dielectric mirrors with low reflectivity at $1.06 \mu\text{m}$ (less than 15%) and high reflectivity at $1.3 \mu\text{m}$. Figure 4 shows the minimum reflectivity required for the output mirror to achieve threshold as a function of the pumping voltage.

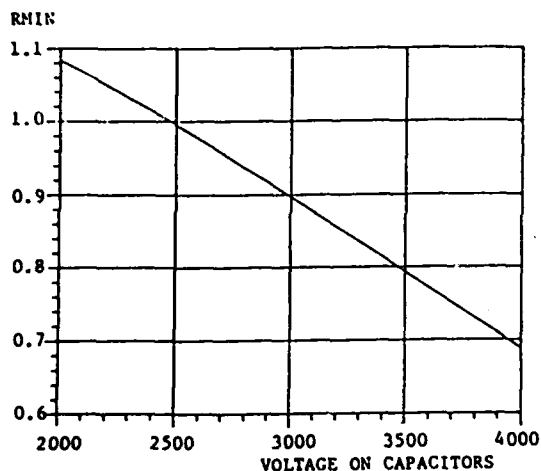


Figure 4

Output Mirror Minimum Reflectivity at $1.3 \mu\text{m}$ is shown for different charging voltages of the 750 μf capacitors for the Space Rays ED-2 oscillator rod with uncoated ends and a 99% rear reflector.

The Space Rays OA-100 laser also has an amplifier 22 cm long, 19 cm in diameter. We are designing an additional amplifier for a 90 cm long, 2.5 cm diameter glass rod. This last amplifier may be necessary in order to get enough energy to do reasonable laser damage tests. If the glass cannot be operated at $1.3 \mu\text{m}$, we are also modifying a pulsed YAG system to operate at $1.3 \mu\text{m}$. The YAG could then serve as the oscillator and the remaining elements as three single-pass amplifiers. We hope to have the laser operational at $1.3 \mu\text{m}$ before Jun 82.

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